

Semiannual Progress Report No. 3

OPTICAL AND RADAR INVESTIGATIONS
OF SIMULATED AND NATURAL METEORS

UNPUBLISHED PRELIMINARY DATA

Research Grant NoG 536

from the

National Aeronautics and Space Administration

15 August, 1964, to 15 February, 1965

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

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OPTICAL AND RADAR INVESTIGATIONS OF SIMULATED AND NATURAL METEORS

I. Some Expectations for the Radar Observations of Artificial Meteors by R. B. Southworth.

Physical regime

Following the results of a previous artificial meteor in 1961 at 10 km/sec (McCrosky and Soberman, 1963), a 2 gram steel pellet will be luminous from about 69 to 63 km altitude. The average number of molecules ablated in that range is therefore 4×10^{16} per cm. A few atmospheric quantities for convenient reference are:

Height (km)	Molecules per cm^3	Molecular mean free path (cm)	T °K	Diffusion coefficient (cm^2/sec)
80	4.0×10^{14}	0.35	185	5.9×10^3
75	9.0×10^{14}	0.16	198	2.7×10^3
70	1.8×10^{15}	0.081	217	1.2×10^3
65	3.5×10^{15}	0.040	239	6.7×10^2
60	6.3×10^{15}	0.022	258	3.7×10^2

The flow of air over the meteoroid will approach a continuum regime, and there will be an accumulation of meteoric and atmospheric gas ahead of the meteoroid. Within a millisecond or so, the column of meteoric gases (including ions and electrons) will reach a radius of several centimeters and be mixed with a larger quantity of atmospheric gases. Then kinetic diffusion will spread the column further, but much more slowly.

When the mean free path in the gas surrounding a meteoroid exceeds the size of the meteoroid, an ablated atom will usually have to be ionized in its first collision with an atmospheric molecule if it is to be ionized

at all, because subsequent collisions will be at much lower relative velocities. This situation prevails for faint fast radio meteors. With the artificial meteor, however, and also for some bright radio meteors, a few of the ablated atoms will undergo repeated collisions at the full meteoric velocity, and can be ionized by stages. Concurrently, there will be some ablated atoms that never collide at the full meteoric velocity. It will be pointed out below that very few atoms will be ionized in a single collision at 10 km/sec. Consequently, the ionizing efficiency at 10 km/sec depends much more on the size of the meteoroid and the atmospheric mean free path than will be the case at higher velocities.

Ionizing efficiency

Verniani and Hawkins (1964) have found from meteor observations that the probability β that an ablated meteor atom will be ionized is approximately

$$\beta = 10^{-28} v^4, \quad (1)$$

where v is the meteor's velocity in cm/sec. They also found that the proportion between the amounts of energy used in ionization and in luminosity is approximately independent of velocity. Nonetheless, their data does not extend below 15 km/sec, and is mostly above 20 km/sec.

The minimum velocity necessary to ionize an atom in its lowest state by a single collision with an N_2 molecule is, for various elements:

Material	Na	Mg	Al	Si	Ca	Fe	Co	Ni	Cu
Ionizing velocity (km/sec)	8.8	10.6	9.1	10.3	8.5	9.0	8.9	8.8	8.2

For nonmetals, the velocity needed is generally higher. In laboratory measurements of ionization cross sections (for example, Bydin and Bukhteev, 1960), it is generally found that the cross section is very small unless the velocity is at least 2 or 3 times the minimum velocity. Meteor spectra

give further evidence of the same effect. Even for high-velocity meteors, these show predominantly low excitation, almost all below 14 e.v., although that level can be reached in single collisions at 13 km/sec. Thus there is very little ionization to be expected from single collisions at 10 km/sec.

Application of equation (1) to the 1961 results yields an electron line density of 4×10^{12} electrons/cm. Application of the empirical relationship between line density and visual magnitude found by McKinley (1961, p. 230) and the observed magnitude of the 1961 artificial meteor yields a line density of $\sim 5 \times 10^{14}$ electrons/cm. (The 1961 artificial meteor was also much brighter than Verniani and Hawkins would have predicted.) Both estimates would be expected to be too high, because the velocity is so near the ionization potential.

The experimental equipment is designed to detect a specular echo from a trail with a line density of $\sim 10^{11}$ electrons/cm in a background of cosmic noise, and a nonspecular echo from a trail with $\sim 5 \times 10^{11}$ electrons/cm. It does not seem likely that the effect of the low velocity alone could reduce the line density to the point where the artificial meteor could not be detected.

If McKinley's relation between luminosity and ionization is applicable to the artificial meteor, the radar can detect a much smaller meteor than the camera. It is also possible that the radar can detect the meteor higher in the trajectory than the camera. Thus it is desirable for the meteor to leave the gun at least 10 km above the expected photographic re-entry. This may increase the observable length of the ionized trail, and therefore the probability of a specular echo.

Fragmentation

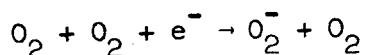
Fragmentation of the artificial meteoroid can affect the radar return in two ways, by changing the total number of electrons produced, and by spreading them out so that the echoes from different parts of the column cancel each other because of phase differences. The second of these can easily prevent radar observation of the meteor. If the meteoroid is divided into n equal fragments, and these are spread laterally by several wavelengths, then the signal returned will be reduced by the factor n . Thus, if the artificial meteor has an appreciable angular width either visually or photographically, one can expect only a very small signal.

The effect of fragmentation on ionizing efficiency has not been studied so far, but is presumably similar to the effect on luminous efficiency. Verniani (1964) concluded that fragmentation reduced luminous efficiency among photographic meteors. If the fragments are small enough that ionization must be caused by single collisions, the ionizing efficiency of the artificial meteor will be severely reduced.

The artificial meteors of November 7, 1964, were 2 to 3 magnitudes fainter than the 1961 artificial meteor, even though they also had much shorter trails. One would expect that the ionization was reduced in at least the same proportion as the luminosity. In addition, the trails had appreciable angular width, so that the radar return would be much further reduced.

Attachment

The dominant process removing free electrons from the atmosphere in the height range of interest is believed to be attachment of the electrons to neutral molecules, primarily O_2 . Students of the atmosphere (Nawrocki and Papa, 1961; Whipple, 1964) accept the three-body reaction



as predominant. The laboratory measure of the rate for gas and electrons at 300°K is (Chanin, Phelps, and Biondi, 1959)

$$n_e^{-1} n_0^{-2} \frac{d}{dt} (n_e) = -2.8 \times 10^{-30} \text{ cm}^6/\text{sec} ,$$

where n_e and n_0 are the number densities of electrons and oxygen molecules. The corresponding line is plotted at the right in Figure 1, which shows various estimates of the time required to reduce the electron density by one power of e as a function of height.

Davis, Greenhow, and Hall (1959a,b) inferred a two-body attachment process from the attenuation or absence of radar meteor echoes. Later, Greenhow and Hall (1961) reinterpreted essentially the same data in terms of a three-body process. Both interpretations have been plotted in Figure 1. The authors recognized the disagreement with published atmospheric attachment rates in both cases, and suggested that there may be additional processes at work in the meteor trails. Possible processes (Nawrocki and Papa, 1961) would be charge transfer and subsequent dissociative recombination, involving molecules present in the meteor trails but not in the normal atmosphere.

Rocket measures of attachment rates by Hodges (1965) appear in the lower right of Figure 1. He has interpreted them as indicating a two-body process, but he cannot explain the discrepancy with known two-body rates, which are much slower than the three-body attachment to oxygen. (He has not noticed the partial agreement with the three-body process.) He notes that contamination by material outgassed from the rocket has not been excluded. Consequently, these measures are best treated as lower bounds.

Successful measures of Fresnel patterns from faint radio meteors by the Harvard Radio Meteor Project down to at least 77 km (Hawkins and

Southworth, 1963) and observations of persistent meteor echoes by the Ottawa three-station network down to at least 80 km (McKinley, 1961, p. 133) place lower bounds on attachment rates. These are plotted in Figure 1. Together with the rocket measures, these lower bounds apparently exclude the three-body interpretation of the meteor data.

The authors themselves suggest (Davis, Greenhow, and Hall, 1959b) that the time constants for the two-body meteor attachment should be increased by a factor of 1.5, and McKinley (1961, p. 229) suggests an increase by a factor of 4. Furthermore, it is quite possible that the unknown process affecting the natural meteors will not affect artificial meteors, because of the difference in composition of the meteoroids (or of the atmosphere, if atomic oxygen is concerned in the natural meteor process).

The height range of the luminosity of an earlier nonfragmenting artificial meteor at 10 km/sec was 69 to 63 km (McCrosky and Soberman, 1963). A similar meteor at 15 km/sec would probably occur roughly 8 km higher, and the radar beginning height might be above the photographic beginning. Possible effects of electron attachment are therefore important to the artificial meteor experiments in that range of heights.

A time constant for electron attachment as small as 0.3^s would probably be just detectable by its effect on a Fresnel pattern of an artificial meteor, assuming that a pattern is observed. A smaller time constant would reduce the echo amplitude to be expected, and a time constant below 0.03^s would probably prevent any observations. However, it does not appear that the electrons will be eliminated fast enough to have any effect on a specular echo.

Observation of a nonspecular echo requires waiting for wind shears to twist the electron trail left by the meteor. The average delay (McKinley, 1961, p. 221) is of the order of one second per 4 degrees of twist, but individual instances vary widely from the mean. From Figure 1, it can be

estimated that the time constant for electron attachment may be of the order of one second. This decreases the probability of observing nonspecular echoes, and therefore decreases the probability of observing artificial meteors more than (say) ten degrees off their intended trajectories in unfavorable directions.

An unintended result of a successful radar observation of an artificial meteor will be a partial or complete resolution of the question of attachment rates.

Conclusions

Interpretation of observations at 10 km/sec requires a careful theoretical study. Observations at 15 km/sec will be much easier and safer to use.

There should be enough ions in an artificial meteor trail to be observed, but the actual number is quite uncertain.

The gun should fire the meteor at least 10 km (preferably more) above the photographic re-entry.

A fragmenting pellet may produce few ions, and they may not constitute a detectable radar target.

Attachment of electrons is probably not a serious problem for this project.

II. Progress Reports

Radar Equipment

Work on the radar transmitter has continued whenever the Range Recoverer has been available. Smithsonian personnel traveled to Bermuda for a 10-day working period in August, since the ship was to be out of Norfolk for $2\frac{1}{2}$ months. During the $2\frac{1}{2}$ months the ship encountered near-hurricane winds. Additional antenna guying had been installed during the day-docking period of July. The antenna was not damaged then and has withstood many rough seas recently.

With the ship back in port during the last half of October, Cambridge engineers, as well as a manufacturer's representative, worked with the radar technicians. By 1 November, natural meteors had been seen and filmed at the receiving sites. The transmitter was then believed to be fully operational with a 100 kw output capability. By the middle of November, however, additional testing showed that the output was still only 10 kw. More modifications were successful in bringing the output to a true 100 kw.

By 1 December, the antenna-matching system permitting simultaneous transmitter and receiver use of the single antenna was installed. The fifth receiving station was also installed on the ship at this time.

Transmitter modifications to adapt this unit, designed for land use, to the rigors of shipboard use continue to the present time. This work is limited by available time in port of the ship. Wallops and Langley support both in landing much test equipment and in arranging ship scheduling for in-port time whenever possible has been invaluable.

The physical installation of the receiver sites along the North Carolina coast was accomplished during the last reporting period.

Extensive guying of all units was completed before the fall hurricane season began. Several storms with winds up to 70 mph swept the sites in September and October. No damage occurred to the antennas or vans.

Air conditioners, heaters, and dehumidifiers have been installed at all sites. Some rusting of camera parts has already occurred in the corrosive, humid atmosphere. It is believed that this has been arrested by continued operation of the dehumidifying equipment.

The radar vans have been extensively modified by removing the old army radar equipment and salvaging many parts for future radar and optical station upgrading. The vans now furnish adequate working and storage areas for our present and future equipment needs.

Optical Equipment

The film-molding system has been continually modified, incorporating safety features as well as temporary cooling methods. A chiller has been designed and will soon be delivered to furnish cold water to the molding head as well as to the processing sink in the darkroom.

A new double-camera hydraulic system has been designed by the Cambridge technical staff and installed at the Wallops site. The two single hydraulic units, formerly at Wallops, have been modified with one now installed at the Eastville site. The other will be installed at Sandbridge with the fourth Super-Schmidt camera.

The ST Super-Schmidt camera, in storage in Cambridge since 1961, was trucked to Wallops by the optical crew in early October. In the following six weeks this camera was extensively modified. An hydraulic opening mechanism, a disk brake, a declination drive motor, and a complete new set of controls and power panels were designed and installed by the optical crew. This work was facilitated by great cooperation from the Wallops instrument machine shop.

By the middle of November, the ST camera was transported to Eastville. With the assistance of a Wallops crane, the SS camera was removed and the ST camera was installed. In December this site was again operational. Focusing and polar adjustments have been continually made up to the present time. Refinements will be made on the physical plant at Eastville as weather permits.

The SS camera was modified in a similar fashion during December. The experience gained during the ST work was invaluable for this second camera work. The SS camera is now ready for the Sandbridge installation.

Construction on the Sandbridge site begun in November will be completed in March. It appears that we may be able to install the SS camera between 15-28 February, if the weather allows sufficient working time for the contractor.

The glass for the new prism was received in January. Manufacture of the prism and the mounting adapter may be completed in March.

Travel

The amount of travel necessary to man and service the eight-station system continues to be a major factor in our operation. The observers' personal vehicles were still used extensively until 15 December, when delivery of our three station vehicles was accomplished.

The two carryalls are proving to be excellent for the long distance of intra-network travel. The four-wheel drive jeep pickup performs very well on the beach trips to the Sandbridge site and also furnishes heavy hauling capacity for both radar and optical equipment.

During heavy schedule times some use of observers' vehicles will be still necessary, but fortunately only a fraction of the former usage.

Personnel

The temporary optical observer resigned 20 August. A permanent assistant observer was hired on 14 October. This man brought the optical complement up to planned strength: 1 supervisor, 2 observers, and 1 assistant observer.

After extensive recruiting, a third radar man was located. This radar supervisor was employed on 23 November, bringing the radar group to its planned strength: 1 supervisor and 2 technicians.

Several local site technicians have been trained and employed occasionally to man the radar site. This method shows great promise for the future.

With the staffing completed, it is now possible to carry out a continuing program of natural observations in addition to our scheduled shots and other Wallops launches.

Network Operation

Sodium-lithium and grenade launches have been observed as well as a Nike-Cajun simulated meteor on 6 November.

The entire network was operational for the 6 November shot. The Wallops and Eastville cameras obtained good data. The radar system obtained recording of a natural meteor at $T + 6$ minutes. Subsequent analysis revealed that the radar transmitter was operating at 1/10 power, as reported. This has since been rectified. The two pellets also diverged substantially from the nominal radiant, probably making radar reflections to our receiver sites unlikely even if full power had been achieved.

The Geminid meteor shower of 12 December was successfully photographed at two receiver sites with enduring meteor trails of up to 30 seconds recorded, as well as many simultaneous meteors between the two sites. The meteor count was in excess of 200/hour.

In January successful radar/optical observations were finally obtained between two optical stations and the Stumpy Point radar-receiver site. It appears that the radar records show Fresnel patterns.

Plans

This data was available for the SAO/Langley conference of 26 January. At this conference the April and November Nike-Cajun shots were thoroughly discussed. Reporting procedures for these shots were agreed upon. Present theoretical concepts were explored and future hardware was planned.

Equipment and shot schedules were recommended for the next six months.

A Nike-Cajun will be launched during the 20 April-6 May period, with an iron dust-ball and a nickel pellet as the two payloads. A Trailblazer will be launched during the 18 June-6 July period, with an iron pellet as a payload. These will be independent shots.

The RT-2 telescope and our Sandbridge camera are desired for the Nike-Cajun shot, but not required. The Trailblazer will not be shot without them, however. In addition, our new prism is necessary for the Trailblazer.

Simultaneous natural meteor records will be obtained whenever possible between the optical and radar systems during the coming months, using various film combinations at various cameras.

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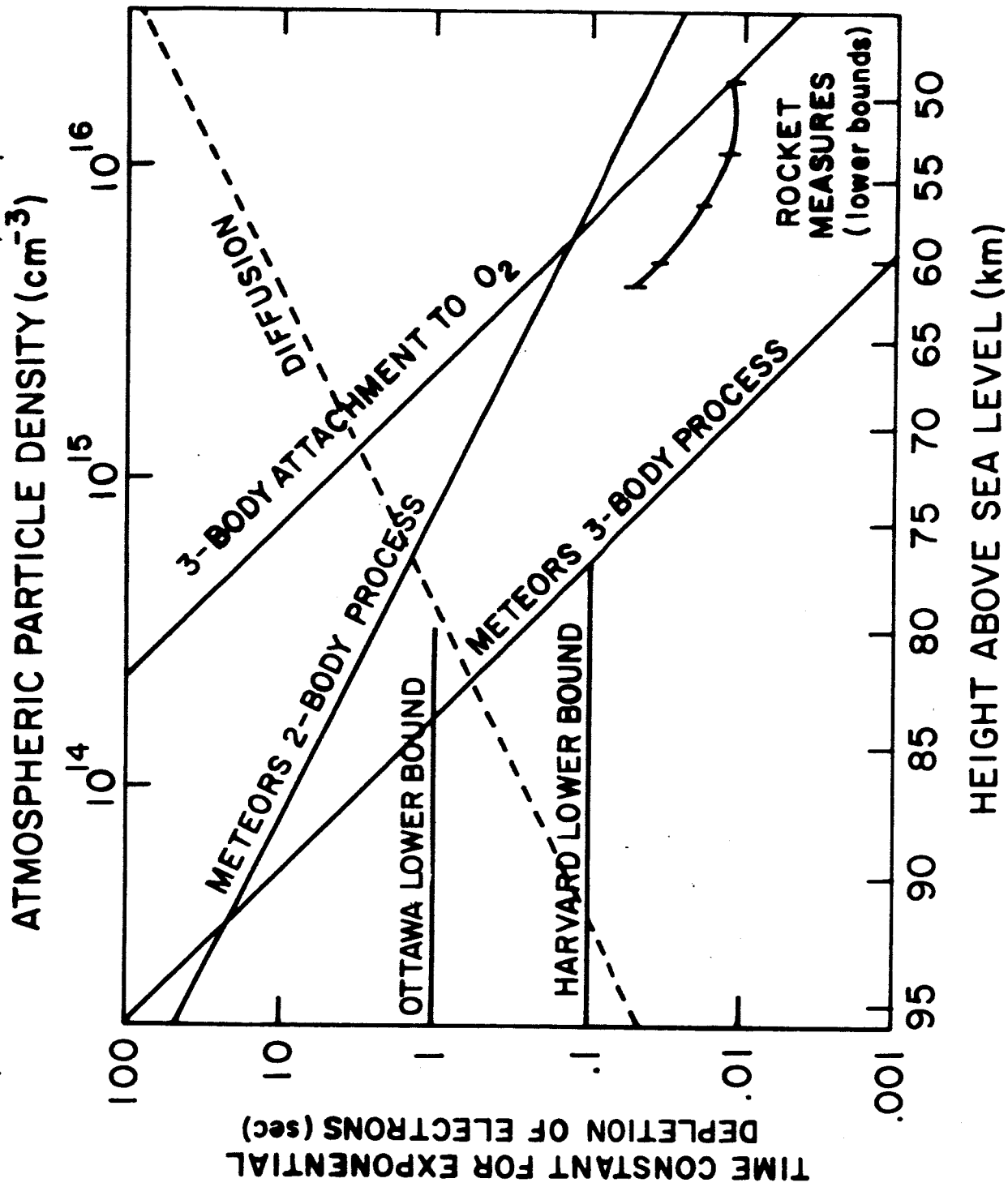


Figure 1.--Theories and observations of the rate at which free electrons are removed from the atmosphere, to determine whether or not they persist long enough to be measured by this project. The apparent loss rate of underdense meteor trails by diffusion has been added for comparison, to show that it will not be important for the artificial meteors.